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Multi-objective optimization of process parameters for 7050 aluminum alloy rib-web forgings' precise forming based on Taguchi method

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Abstract

The precision forming of rib-web forgings can effectively increase strength and toughness of forgings and improve material utilization simultaneously. However, inappropriate selection of process parameters can cause defects such as under-filling, cross flow, and etc. Thus the optimization of process parameters is essential for getting good products. In this paper, we combined the finite element method with Taguchi method to optimize the precision forming process of rib-web forgings through multi-objective design. The macro-and microstructure of products were used to verify the result of simulation. The flow line microstructure and the die-fill quality were chosen as optimal objectives; and, the optimal combination of parameters for the analyzed process window was obtained through the variance analysis and signal-to-noise ratio analysis of the simulation results. The results suggest that initial temperature and height-width ratio of the billet are the most crucial factors affecting the forging quality in the analyzed area. In addition, the optimal combination of parameters is A4 (450 °C) B1 (0.1 mm/s) C4 (H / B =5) and D3 (μ = 0.3). Finally, the production experiment verified the prediction quite well, which confirmed the effectiveness of the proposed optimization method.

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Keywords: Rib-web forgings; Taguchi method; Multi-objective optimization; Precision forming

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1. Introduction

Aluminum alloy forgings are widely used in aeronautic industry. To meet the demand of weight reduction, Sun and Yang (2009) [1] argue that this kind of parts is usually designed to be thin web with vertical and horizontal ribs, which makes it very difficult to process. Folding, under-filling, cross flow, and other defects usually occur during the forming process by Zhang et al. (2010) [2]. For large-scale rib-web forgings with high usability requirement, forging or rolling are often used to get preforms and then the ribs are usually got by NC Machining or milling process. Those methods have many disadvantages such as low material utilization, high processing cost, environmental pollution and so on. What's worse, metal streamline on the strengthening ribs will be incised, which lowers the strength of parts considerably and invalidate the parts. With the widespread use of rib-web forgings, to find a low-cost and efficient processing methods is significant. The development of precise forming technology has contributed a lot to the processing of this kind of parts found by Yoshimura et al. (2000) [3] and Bewlay et al. (2003) [4] and Gao et al. (2003) [5].

The settings of process parameters are the most important factor in precise forming process and how to get the optimal combination of parameters for specialized parts is the focus of current research. Nowadays, many researchers combine the finite element simulation and various optimization algorithms to find the optimal combination of parameters. Wei et al. (2011) [6] combined the Taguchi method and finite element simulation to do the multi-objective optimization of process parameters of precision forging process of helical gears. By combining FEM, sensitivity analysis and optimization method, Guan et al. (2008) [7] optimized the microstructure evolution of the forging process and the shape of preforms were chosen as optimized objects. Yang et al. (2009) [8] chose turbine disk of aero engine as the research object and used response surface method and FEM to research the multi-objective optimization of preform design. In this paper, one aeronautic rib-web forging was chosen as research object. We designed our experiments by combining Taguchi method and FEM and then figured out the signal-to-noise ratio of each control parameter. By conducting variance analysis and signal-to-noise ratio analysis of signal-to-noise ratio results, we can get the optimal levels and the extent of impact of each parameter and then get the optimal combination of parameters for our analyzed process.

2. Experimental design by Taguchi Method

DOE is a kind of system approach researching experimental system or experimental process. By testing the change of a series of parameters of the system or process, we get their impacts on output. The Taguchi Method was proposed by Taguchi in 1950's and Taguchi's ideas of parameter design was to reduce the variance and reduce the bias. Instead of changing one parameter once, using Taguchi Method to design experiment can verify individual impact and interactive influence of each parameter which was used by Oktem et al. (2007) [9] .

2.1. Orthogonal experimental design

To research the impact of each parameter on the experimental result, we used L16 orthogonal array to do the experimental design. Table 1 shows forming parameters and levels.

Table 1. Forming parameters and levels.

Symbol	Parameters	Level 1	Level 2	Level 3	Level 4
A	Billet temperature T(°C)	300	350	400	450
B	Forging velocity V(mm/sec)	0.1	0.2	0.3	0.4
C	H/B of billet	2	3	4	5
D	friction coefficient μ	0.1	0.2	0.3	0.4

2.2. Design of objective function

Some common defects of rib-web forging processing include under-filling, inhomogeneous forming, fiber break and so on. The difference between real forgings and ideal forgings was chosen as the evaluation index of filling properties and the objective function is as below:

$$\psi = \sum_{j=1}^{N} A_j^2 . \quad (1)$$

A_j is the mismatching area of real forgings and ideal forgings; N is the total number of elements.

We chose the quadratic sum of the difference of random strain and average strain as the evaluation index of the forming homogeneity and the objective function is as below:

$$\zeta = \sum_{i=1}^{N} \left(\bar{\varepsilon}_i - \bar{\varepsilon}_{avg} \right)^2 . \quad (2)$$

$\bar{\varepsilon}_i$ is the random equivalent strain; $\bar{\varepsilon}_{avg}$ is the average equivalent strain; N is the total number of elements.

The average velocity of metal flow towards flange in web section when the processing is almost over was chosen as the evaluation index of fiber break and the objective function is as below:

$$\bar{V} = \frac{1}{N} \sum_{i=1}^{N} V_i . \quad (3)$$

V_i is the velocity of metal flow towards flange in web section; N is the total number of elements.

3. Experimental results and parameter optimization

3.1. Orthogonal experimental results.

According to the parameters and L16 orthogonal array we chose, we got the results of numerical simulation in Table 2. S/N follows “the smaller-the-better” standard of Taguchi Method and its calculation formula is as below:

$$S/N = -10 \log_{10} \left(\frac{1}{n} \sum_{1}^{n} \frac{1}{y_i^2} \right). \quad (4)$$

y_i is the experimental results; n is the experimental number. S/N can not only insure the average value closing to the nominal value, but also reduce the fluctuation.

Table 2. Results of orthogonal experiment.

Exp No.	ψ (mm2)	ζ	V (mm/s)	S/N
1	0	3.04	688.4	61.53
2	0	3.07	575.2	59.97
3	0	3.12	571.5	59.91
4	1.22	1.61	659.6	61.16
⋮	⋮	⋮	⋮	⋮
13	0	3.16	1328.3	67.24
14	0	3.15	1157.5	66.04
15	3.35	1.68	943.2	64.26
16	0	2.87	775.2	62.56

3.2. Parameter optimization

By conducting variance analysis and signal-to-noise ratio analysis of orthogonal experiment results, we can get the optimal levels and the extent of impact of each parameter and then get the optimal combination of parameters for our analyzed process. Table 3 is the variance analysis table of experimental results. From table 3 we can see that factor A (billet temperature) has the most obvious impact on the quality of forgings which is followed by factor C (H/B of billet). On the contrary, factor B (forging velocity) and factor D (friction coefficient) shows non-significant influence on the quality of forgings.

Table 3. Variance analysis table.

source of variation	quadratic sum	degree of freedom	Mean squared error	F value	significance
Factor A	41.61	3	13.87	33.16	*
Factor B	4.37	3	1.46	3.48	
Factor C	13.72	3	4.57	10.93	(*)
Factor D	4.16	3	1.39	3.31	
error	1.25	3	0.42		
sum	65.11	15			

Fig. 1 is the response diagram of S/N which shows the impact trend on experimental results of each parameter and the best parameter occurs at the peak point of S/N. The diagram demonstrates that the optimal combination of parameters is A4B1C4D3.

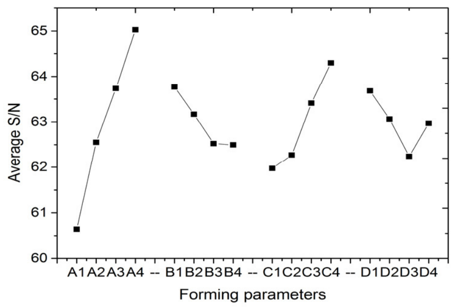

Fig. 1. Response diagram of S/N.

4. Experimental verification

To verify the optimal combination of parameters, we used FEM and production experiment. Fig. 2. shows part of the forgings of our production experiment based on the optimal combination of parameters and the forgings fill well and have smooth surface. In addition, we have done some contrastive analysis of metal flow before and after the optimization. From Fig. 3, we can see that the average velocity of the metal flow in web section towards flange decrease considerably from 16.4 mm/s to 3.6 mm/s, which illustrates that the optimal combination of parameters can smoothen the metal flow of processing. Thus, fewer streamline defects such as flow-through, fiber break and so on come into being.

Fig. 2. Parts drawing.

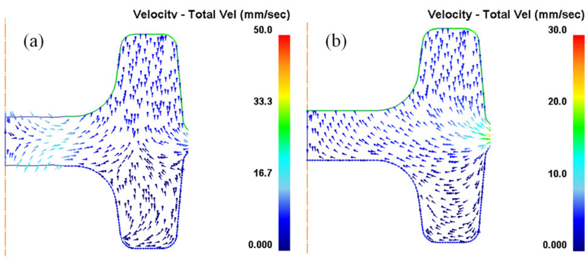

Fig. 3. Distribution of velocity for (a) before optimization and (b) after optimization.

5. Conclusions

(1) Under-filling, flow-through and some other defects are chosen as the optimization objective of 7050 aluminum alloy rib-web forgings' precise forming. Billet temperature, forging velocity, H/B of billet and friction coefficient are parameters going to be optimized for the analyzed process. From the experimental results we know that all the parameters chosen have some impact on the quality of forgings. However, billet temperature demonstrates the most obvious influence on quality and H/B of billet follows it. Forging velocity and friction coefficient have non-significant impact on the quality.

(2) By conducting variance analysis and signal-to-noise ratio analysis of orthogonal experiment results, we can get the optimal combination of parameters for analyzed process is: A4 (450 °C) B1 (0.1 mm/s) C4 (H/B = 5) and D3 (μ = 0.3).

(3) FEM and production experiment are used to confirm the optimal combination of parameters which verify its reliability.

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